HIGH EFFICIENCY INDUCTION HEATING AND MELTING SYSTEMS

Cross-reference to Related Applications

[0001] This application is a continuation-in-part of U.S. application serial no. 10/135,271, filed April 29, 2002, which is a continuation-in-part of application serial no. 09/550,305, filed April 14, 2000, now U.S. Patent 6,393,044 and also claims priority to provisional patent application serial no. 60/165,304, filed November 12, 1999, the entirety of each of which are incorporated herein by reference.

Field of the Invention

[0002] The present invention relates to induction heating and melting systems that use magnetic induction to heat a crucible in which metal or other materials can be heated and/or, melted and held in the molten state by heat transfer from the crucible.

Background of the Invention

[0003] Induction melting systems gain popularity as the most environmentally clean and reasonably efficient method of melting metal. In the induction melting furnace **1** shown in **FIG. 1**, the electromagnetic field produced by AC current in coil **2** surrounding a crucible **3** couples with metal or other conductive materials **4** inside the crucible and induces eddy currents **5**, which in turn heat the metal. As indicated in **FIG. 1**, the arrows associated with coil **2** generally represent the direction of current flow in the coil, whereas the arrows associated with eddy currents **5** generally indicate the opposing direction of induced current flow in the conductive materials. Variable high frequency ac (typically in the range from 100 to 10,000 Hz) current is generated in a power supply or in a power converter **6** and supplied to coil **2**. The converter **6**, typically but not necessarily, consists of an AC-to-DC rectifier **7**, a DC-to-AC inverter **8**, and a set of capacitors **9**, which, together with the induction coil, form a resonant loop. Other forms of power supplies, including motors-generators, pulse-width modulated (PWM) inverters, and the like, can be used.

[0004] As shown in **FIG. 2**, the magnetic field causes load current **10** to flow on the outside cylindrical surface of the conductive material, and coil current **11** to flow on the inner surface of the coil conductor. Crucible **3** in a typical furnace is made from ceramic material and usually is not electrically conductive. The efficiency of the furnace is computed by the formula:

$$\eta = \frac{1}{1 + \frac{D_1}{D_2} \bullet \frac{\rho_1}{\rho_2} \bullet \frac{\Delta_2}{\Delta_1}} \qquad \text{equation (1)}$$

[0005] where

[0006] η = furnace efficiency;

[0007] D_1 = coil inner diameter;

[0008] D_2 = load outer diameter;

[0009] ρ_1 = resistivity of coil winding material (copper);

[0010] ρ_2 = resistivity of load (melt);

[0011] Δ_1 = current depth of penetration in copper winding; and

[0012] Δ_2 = current depth of penetration in load (melt).

[0013] The depth of current penetration (Δ) is a function of a material's properties as determined by the formula:

$$\Delta = k \bullet \sqrt{\frac{\rho}{f \bullet \mu}} \qquad \text{equation (2)}$$

[0014] where:

[0015] ρ = resistivity in ohm•meters;

[0016] f = frequency in Hertz;

[0017] μ = magnetic permeability (dimensionless relative value); and

[0018] Δ = depth of penetration in meters.

[0019] The constant, k = 503, in equation (2) is dimensionless.

[0020] Because current does not penetrate deep into the low resistivity copper material of the coil, the typical coil efficiency is about 80 percent when the molten material is iron. Furnaces melting low resistivity materials such as aluminum (with a typical resistivity value of 2.6×10^{-8}

ohm•meters), magnesium or copper alloys have a lower efficiency of about 65 percent. Because of significant heating due to electrical losses, the induction coil is water-cooled. That is, the coil is made of copper tubes **12** and a water-based coolant is passed through these tubes. The presence of water represents an additional danger when melting aluminum, magnesium or their alloys. In case of crucible rupture, water may combine with molten aluminum and a violent chemical reaction may take place in which the aluminum combines with oxygen in the water, releasing free hydrogen which may cause an explosion. Contact between water and magnesium may similarly result in an explosion and fire. Extreme caution is taken when aluminum or magnesium is melted in conventional water-cooled furnaces.

[0021] An object of the present invention is to improve the efficiency of an induction furnace by increasing the resistance of the load by using as the load a crucible made of a high temperature electrically conductive material or a high temperature material with high magnetic permeability. It is another object of the present invention to improve the efficiency of an induction furnace by reducing the resistance of the induction coil by using as the coil a cable wound of multiple copper conductors that are isolated from each other. It is still another object of the invention to properly select operating frequencies to yield optimum efficiency of an induction furnace.

[0022] It is a further object of the present invention to provide a high efficiency induction melting system with a furnace and power supply that do not use water-cooling and can be efficiently air-cooled.

Summary of the Invention

[0023] In its broad aspects, the present invention is an induction furnace that is used for melting a metal charge. The furnace has a crucible formed substantially from a material having a high electrical resistivity or high magnetic permeability, preferably a silicon carbide or a high permeability steel. At least one induction coil surrounds the crucible. The coil consists of a cable wound of a plurality of conductors isolated one from the other. An isolation sleeve electrically and thermally insulates the crucible from the at least one induction coil. Preferably, the isolation sleeve is a composite ceramic material, such as an air-bubbled ceramic between two layers of ceramic. In alternate examples of the invention, the induction furnace is used to heat the metal charge to a temperature that may be below its melting point.

[0024] Copper is especially preferred for the conductors, because of its combination of reasonably high electrical conductivity and reasonably high melting point. A preferred form of

the cable is Litz wire or litzendraht, in which the individual isolated conductors are woven together in such a way that each conductor successively takes all possible positions in the cross section of the cable, so as to minimize skin effect and high-frequency resistance, and to distribute the electrical power evenly among the conductors.

[0025] In another aspect, the present invention is an induction melting system that is used for melting a metal charge. The system has at least one power supply. The crucible that holds the metal charge is formed substantially from a material having a high electrical resistivity or high magnetic permeability, preferably a silicon carbide or a high permeability steel. At least one induction coil surrounds the crucible. The coil consists of a cable wound of a large number of copper conductors isolated one from the other. An isolation sleeve electrically and thermally insulates the crucible from the at least one induction coil. Preferably, the isolation sleeve is a composite ceramic material, such as an air-bubbled ceramic between two layers of ceramic. Preferably, the induction melting system is air-cooled from a single source of air that sequentially cools components of the power supply and the coil. The metal charge is placed in the crucible. Current is supplied from the at least one power supply to the at least one coil to heat the crucible inductively. Heat is transferred by conduction and/or radiation from the crucible to the metal charge, and melts the charge. In alternate examples of the invention, the induction furnace is used to heat the metal charge to a temperature that may be below its melting point.

[0026] In another aspect, the present invention is an induction heating system that is used to heat, melt, vaporize, and/or otherwise alter the physical state of a workpiece or material by heating. The system has at least one power supply. The crucible that holds the workpiece or material is formed substantially from a material having a high electrical resistivity or high magnetic permeability, preferably a silicon carbide or a high permeability steel. At least one induction coil surrounds the crucible. The coil consists of a cable wound of a large number of copper conductors isolated one from the other. An isolation sleeve electrically and thermally insulates the crucible from the at least one induction coil. Preferably, the isolation sleeve is a composite ceramic material, such as an air-bubbled ceramic between two layers of ceramic. Preferably, the induction melting system is air-cooled from a single source of air that sequentially cools components of the power supply and the coil. The workpiece or material is placed in the crucible. Current is supplied from the at least one power supply to the at least one coil to heat the crucible inductively. Heat is transferred by conduction and/or radiation from the crucible to the workpiece or material in the crucible, and heats, melts, vaporizes and/or otherwise alters the physical state of the workpiece or charge by the conducted and/or radiated heat.

[0027] These and other aspects of the invention will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] For the purpose of illustrating the invention, there is shown in the drawings a form which is presently preferred; it being understood, however, that this invention is not limited to the precise arrangements and instrumentalities shown.

[0029] **FIG. 1** is a diagrammatic representation of a prior art induction melting system that includes a furnace and power supply converter.

[0030] **FIG. 2** is a cross sectional elevation view of a prior art induction coil of copper tubes around a crucible that has a conductive material inside of the crucible.

[0031] **FIG. 3** is a cross sectional elevation view showing the distribution of current in an electrically conductive high resistance crucible used in the induction furnace of the present invention.

[0032] **FIG. 4(a)** is a perspective view of a wound cable composed of twisted multiple copper conductors that is used in the induction furnace of the present invention.

[0033] **FIG. 4(b)** is a cross sectional view of the wound cable shown in **FIG. 4(a)**.

[0034] **FIG. 4(c)** is a cross sectional view of one of the insulated copper conductors that make up the wound cable.

[0035] **FIG. 5(a)** is a cross sectional elevation view of an induction furnace of the present invention with a high electrical resistance crucible and an induction coil of the wound cable shown in **FIG. 4(b)**.

[0036] **FIG. 5(b)** is a cross sectional detail of one embodiment of the isolation sleeve shown in **FIG. 5(a)**.

[0037] **FIG. 5(c)** illustrates the airflow through the power supply and induction coil for the induction melting or heating systems of the present invention.

[0038] **FIG. 6** is an electrical schematic of the power circuit for one embodiment of the induction melting or heating systems of the present invention.

[0039] FIG. 7 is a perspective view of an induction tunnel heating system of the present invention for heating a workpiece.

[0040] FIG. 8 is a perspective view of another induction tunnel heating system of the present invention for heating a workpiece.

[0041] FIG. 9 is a perspective view of an enclosed induction heating system of the present invention for heating a workpiece.

[0042] FIG. 10 is a perspective view of another enclosed induction heating system of the present invention for heating a workpiece.

[0043] FIG. 11(a) is a perspective view of another induction tunnel heating system of the present invention.

[0044] FIG. 11(b) is a perspective view of another induction tunnel heating system of the present invention.

[0045] FIG. 11(c) is a perspective view of another induction tunnel heating system of the present invention.

Detailed Description of the Invention

[0046] The efficiency of an induction furnace as expressed by equation **(1)** and equation **(2)** above, can be improved if the resistance of the load can be increased. The load resistance in furnaces melting highly conductive metals such as aluminum, magnesium or copper alloys, may be increased by coupling the electromagnetic field to the crucible instead of to the metal itself. The ceramic crucible may be replaced by a high temperature, electrically conductive material with high resistivity factor. Silicon carbide (SiC) is one of the materials that has these properties, namely a resistivity generally in the range of 10 to 10^4 ohm•meters. Silicon carbide compositions with resistivity in the approximate range of 3,000 to 4,000 ohm•meters are particularly applicable to the present invention. Alternatively, the crucible may be made from steel. For example, there are high permeability ferromagnetic steels with relative permeabilities in the range of 5,000. In this case, rather than relying on high resistivity, the high permeability will result in low depth of current penetration. As the steel is heated its permeability will drop. **FIG. 3** shows the distribution of current **28** in the crucible **27** that will produce the effect of high total resistance. The best effect is achieved when the wall thickness of the crucible is about 1.3 to 1.5 times larger

than the depth of current penetration into the crucible. In this case, the shunting effect of highly conductive molten metal **29** is minimized.

[0047] An additional improvement in the efficiency of an induction furnace can be achieved by reducing the resistance of the coil. High conductivity copper is widely used as the material for a coil winding. However, because of the high conductivity (low resistivity) of the copper, the current is concentrated in a thin layer of coil current **11** on the surface of the coil facing the load, as shown in **FIG. 2**. The depth of current penetration is given by equation **(2)**. Because the layer is so thin, especially at elevated frequencies, the effective coil resistance may be considerably higher than would be expected from the resistivity of copper and the total cross-sectional area of the copper coil. That will significantly affect the efficiency of the furnace. Instead of using a solid tubular conductor, one embodiment of the present invention uses a cable **17** wound of a large number of copper conductors isolated one from another, as shown in **FIGS. 4(a)**, **4(b)** and **4(c)**. One of the insulated copper conductors **14** is shown in **FIG. 4(c)** with the insulation **16** that isolates the copper conductor **15** from surrounding conductors. The cable **17** is of the sort known in the electronic industry as Litz wire or litzendraht. It assures equal current distribution through the copper cross section when the diameter of each individual copper wire strand is significantly smaller than the depth of current penetration Δ_1 as given by equation **(2)**. For the present application, a suitable but not limiting number of strands is approximately between 1,000 and 2,000. Other variations in the configuration of the Litz wire will perform satisfactory without deviating from the present invention.

[0048] The proper selection of operating frequencies yields optimum efficiency of an induction furnace. The criteria for frequency selection are based on depth of current penetration in the high resistance crucible and copper coil. The two criteria are:

[0049] $\Delta_1 \gg d_1$; and

[0050] $\Delta_2 \approx 1.2 \bullet d_2$

[0051] where:

[0052] d_1 = diameter of a strand of Litz wire; and

[0053] d_2 = wall thickness of the crucible.

[0054] For example, when the copper strand diameter is d_1 = 0.01 inch and the silicon carbide wall thickness is d_2 = 2.0 inches, the optimal frequency is 3,000 Hz. With this selection, the

relative electrical losses in the coil may be reduced to about 2.2%, which is more than 15 times better than a standard induction furnace.

[0055] Acceptable, but not limiting, parameters for a furnace in accordance with the present invention is selecting d_1 in the range of 0.2 to 2.0 meters, d_2 in the range of 0.15 to 1.8 meters, and frequency in the range of 1,000 to 5,000 Hertz.

[0056] Such an increase in efficiency or reduction in coil losses, and thus reduction in heating of the coil, eliminates the need for a water-based cooling system. Instead, a reasonable airflow through the induction coil is sufficient to remove the heat generated by the coil. The furnace crucible should be well insulated from the coil to minimize thermal losses and heating of the copper winding due to thermal conduction.

[0057] Referring now to the drawings, wherein like numerals indicate like elements, there is shown in **FIG. 5(a)** an embodiment of a high-efficiency induction melting system **33** in accordance with the present invention. The induction melting system **33** includes a high electrical resistance or high magnetic permeance crucible **30** containing metal charge **31**. The high resistance or high permeance is achieved by using a crucible made from a high resistivity material ($\rho > 2500$ $\mu\Omega$•cm) like silicon carbide or from a high permeability steel ($\mu > 20$), respectively. The selection of crucible material depends on the properties of the metals to be melted. For aluminum or copper alloys, silicon carbide is a better crucible material, while for magnesium or magnesium alloys, steel may be a better choice for the crucible material. The crucible **30** is heated by the magnetic field generated by current in the coil **32**, which is made with Litz wire. The hot crucible is insulated from the coil electrically and thermally by an isolation sleeve **34**. The isolation sleeve is constructed from a high strength composite ceramic material containing one or more inner layers **35** and outer layers **36** filled with air-bubbled ceramic **37** with good thermal insulation properties. The honeycomb structure of the isolation sleeve provides necessary strength and thermal isolation. The electrically insulating nature of the isolation sleeve, together with its low magnetic permeability, ensures that no appreciable inductive heating takes place in the isolation sleeve itself. That concentrates the heating in the crucible **30**, inside the thermal insulation of the isolation sleeve **34**, which both improves the efficiency of the induction melting system **33** and reduces heating of the coil **32**.

[0058] One embodiment of the invention includes a power converter **39** that converts a three-phase standard line voltage such as 220, 280 or 600 volts into a single phase voltage with a frequency in the range of 1,000 to 3,000 Hz. The power converter may include power

semiconductor diodes **41**, silicon controlled rectifiers (SCR) **40**, capacitors **42**, inductors **43** and **46**, and control electronics. The schematic diagram of one implementation of the power converter is shown in **FIG. 6**. In **FIG. 6**, diodes **41** in the rectifier bridge are optionally provided in dual-diode modules. Inductor **43** serves as a choke, and inductors **46** are di/dt reactors. SCRs **40** and associated anti-parallel diodes **41** are suitably connected to heat sinks. All of the semiconductor components of the power converter are air-cooled via heat exchangers **44** (shown in **FIG. 5(a)**), such as heat sinks. Other inverter circuits and/or electromechanical systems can be used.

[0059] In one embodiment of the invention, the power converter **39** is mounted adjacent to the induction coil **32**. As shown in **FIG. 5(a)** and **FIG. 5(c)**, an airflow **47** (as illustrated by arrows from an external blower **45**) is fed to the power converter where the cold air first cools the semiconductors' heat exchangers **44**, and then the capacitors, inductors and other passive components. The converter cabinet is positively pressurized to prevent dust and other particulate from entering the electronics compartments. The airflow exits through a slot **48** in the back wall of the power supply **39**, and enters and flows through the coil chamber **38** to remove heat from the coil. In **FIG. 5(c)**, for clarity in illustrating the airflow **47** through the induction melting system, the induction melting system **33** is outlined in phantom.

[0060] In an alternative embodiment as shown in **FIG. 7**, a high-efficiency induction heating system **33a** in accordance with the present invention, is in the form of a tunnel furnace through which multiple discrete workpieces, or a continuous workpiece **90**, such as a metal strip, wire or other object to be heated, can be run through the furnace by a mechanical conveying system (not shown in the drawing) in the direction indicated by the arrows. In this embodiment, the furnace tunnel crucible **30a**, is surrounded by isolation sleeve **34a**. Coil **32a** is coiled around the exterior of isolation sleeve **34a** and connected to a suitable power supply converter (not shown in **FIG. 7**). Crucible **30a**, isolation sleeve **34a**, coil **32a** and the power supply converter are similar to crucible **30**, isolation sleeve **34**, coil **32**, and power converter **39** disclosed in other examples of the invention. Ac current supplied from the power converter to the coil that comprises a cable wound of a plurality of conductors isolated from each other will generate a magnetic field that inductively heats the crucible. Heat generated in the crucible will conduct into the tunnel of the furnace and heat workpieces within the tunnel.

[0061] **FIG. 8** illustrates an alternative embodiment of a high-efficiency induction heating system **33b** of the present invention wherein the tunnel furnace utilizes a conveyor means **91** to

move workpieces **94a** and **94b** through the crucible of the tunnel furnace. Not shown in **FIG. 8** within the enclosure of the tunnel furnace is crucible **30a**, isolation sleeve **34a** and coil **32a**, which are generally arranged as illustrated in **FIG. 7**. Optionally a power supply or converter, similar to power converter **39**, may be included in the enclosure of the tunnel furnace. The supply may, for example, be located in bottom section **93** of the enclosure. For this option, a forced airflow can be drawn into the bottom of the enclosure to first cool components of the power converter, and then directed upwards around the coil to cool the coil. The heated air exits the enclosure through openings **95** in its top.

[0062] In another alternative embodiment as shown in **FIG. 9**, a high-efficiency induction heating system **33c** in accordance with the present invention, is in the form of an enclosed furnace in which one more discrete workpieces **94** can be heated. The crucible **30a**, isolation sleeve **34a** and coil **32a** are similar to crucible **30**, isolation sleeve **34** and coil **32** disclosed in other examples of the invention. Furnace first end structure **92** is attached to crucible **30a** to form the first closed end of the furnace's closed heating chamber. Furnace second end structure **98** is removably attached to the opposing end of crucible **30a**. The first and second end structures **92** and **98** are composed of a thermal insulating material, such as but not limited to, the disclosed material for the isolation sleeve. Suitable support means **96**, such as a grating composed of a non-electrically conductive and high temperature withstand material, can be provided inside the heating chamber to support the workpieces. After insertion of the workpieces into the heating chamber, removably attached second end structure **98** is attached to the opposing end of crucible **30a** to close the heating chamber. Ac current is supplied from a suitable source to coil **32a**. The current generates a magnetic field in the coil that comprises a cable wound of a plurality of conductors isolated from each other that inductively heats crucible **30a**. The heat generated in the crucible conducts into the enclosed heating chamber to heat workpiece **94** within the chamber.

[0063] FIG. 10 illustrates another arrangement of a high-efficiency induction heating system **33d** of the present invention using a furnace with an enclosed heating chamber. Not shown in **FIG. 10** and within the enclosure of the furnace, is crucible **30a**, isolation sleeve **34a**, furnace first end structure **92** and coil **32a**, which are generally arranged as illustrated in **FIG. 9**. In the arrangement shown in **FIG. 10**, furnace second end structure **98a** comprises a circular component that is attached by a hinged element to the enclosure. A power supply or converter, similar to power converter **39**, may be optionally included in the enclosure of the furnace. The supply may, for example, be located in bottom section **93a** of the enclosure. For this option, a forced airflow can be drawn into the bottom of the enclosure to first cool components of the

power converter, and then directed upwards around the coil to cool the coil. The heat exits the enclosure through openings **95a** in its top.

[0064] FIG. 11(a) illustrates another arrangement of a high-efficiency induction heating system **33e** of the present invention wherein crucible **30a** rotates about its longitudinal axis (X) by means of a suitable rotational drive such as, but not limited to, electric motor **80** with its output shaft suitably connected to a crucible rotating element. By way of example and not limitation, one method of connecting the rotational drive means to the crucible is shown in **FIG. 11(a)**. The output shaft of electric motor **80** is connected to the outer perimeter of crucible **30a** by belt **81**. The crucible is tunnel-shaped and preferably cylindrical. Crucible **30a**, isolation sleeve **34a** and coil **32a** are similar to crucible **30**, isolation sleeve **34** and coil **32** disclosed in other examples of the invention. One or more workpieces or other material can be inserted into the crucible at either end of the crucible by means of a suitable external feed material conveyor means. As in other examples of the invention crucible **30a** is heated by the magnetic field generated by current in coil **32a**. The one or more workpieces or other material placed in the crucible are heated by the transfer of heat from the crucible.

[0065] In some examples of the invention isolation sleeve **34a** may be attached to the crucible so that it rotates with the crucible. In those examples the coil is preferably separate from the isolation sleeve so that the coil does not rotate with the crucible.

[0066] In some examples of the invention the longitudinal axis of the crucible is substantially horizontally oriented so that the material in the crucible does not significantly advance along the longitudinal axis of the crucible as it is heated. In other examples of the invention the longitudinal axis of the crucible may be skewed relative to horizontal so that the material placed in one end of the crucible advances along the length of the crucible as the crucible rotates and the material is heated.

[0067] Optionally as shown in **FIG. 11(b)** (partial cross sectional view with coil **32a** removed for clarity) a means for advancing the material through the crucible as the crucible rotates, such as one or more conveying elements **82** can be provided. Conveying element **82** provides a means for advancing one or more workpieces or material inside the crucible along the length of the crucible by forcing movement of the material along the crucible's longitudinal length or axis as the crucible rotates. The one or more conveying elements may consist of a continuous structural element or series of discrete structural elements rising from the interior wall of the crucible. By way of example and not limitation conveying elements may be a unitary or segmented helically

wound protrusion(s) rising from the interior wall of the crucible. If crucible **30a** is castably formed, the conveying elements may be cast integrally with the crucible. Otherwise the conveying elements may be discretely fitted on the interior wall. As the crucible rotates the material advances along the longitudinal length of the crucible by coming in contact with the one or more conveying means on the inner wall of the crucible. As the material advances along the longitudinal length of the crucible it is further heated until it reaches the exit end of the crucible.

[0068] In some applications the material being heated inside the crucible will have a tendency to adhere to the interior wall of the crucible as it is heated. In those applications induction heating system **33e** can be provided with a means for vibrating the crucible to loosen any material sticking to its interior wall. The means for vibrating the crucible may be a weight fastened at one end of a flexible connecting element, such as a chain, that is fastened at its opposing end to the interior of crucible **30a** so that as the crucible rotates, the weight periodically strikes the interior wall of the crucible by centrifugal motion about the chain length to vibrate the crucible and shake material from its interior wall. In other examples of the invention the means for vibrating the crucible may be accomplished by placing the crucible on flexible mounts and connecting a mechanical shaking device that either continuously or periodically shakes the crucible on the flexible mounts.

[0069] In some applications it may be desirable to seal the interior of the crucible from the external environment, for example, when the material in the crucible is heated to a temperature that creates a combination of gas and solid products that may be hazardous materials. For these applications of the invention, as diagrammatically shown in **FIG. 11(c)**, end caps **86a** and **86b** seal the ends of crucible **30a** from the external environment. Rotational seals **87** permit rotation of crucible **30a** while end caps **86a** and **86b** remain fixed. Material can be fed into a sealed first end of the crucible, for example, at end cap **86a** via an external material feed conveyor means. An air lock, or other means, may be provided to keep the interior of the crucible sealed from the external environment as material is fed into the crucible. If required gas products may be evacuated from the sealed interior of the crucible by exhaust port **88**, which can include a one-way check valve to keep the interior of the crucible sealed from the external environment. If required solid products may be fed (typically but not by way of limitation by gravity) from the interior of the crucible at the exit end of the crucible by chute **89**, which can employ an air lock to keep the interior of the crucible sealed from the external environment.

[0070] The high-efficiency induction heating systems shown in **FIG. 11(a), FIG. 11(b)** and **FIG.11(c)** may be suitably housed in either of the enclosures illustrated in **FIG. 8** or **FIG. 10** with appropriate modifications as required to accommodate optional inclination of the crucible and/or opened or closed crucible ends. In these arrangements the high-efficiency induction heating systems shown in **FIG. 11(a), FIG. 11(b)** and **FIG.11(c)** can include an integral power supply for **coil 32a** that is air-cooled as further disclosed above in previous examples of the invention. For these options, a forced airflow can be drawn into the bottom of the enclosure to first cool components of the power converter, and then directed upwards around the coil to cool the coil.

[0071] The terms "workpiece" or "material" as used herein are not intended to be limiting to any particular type of workpiece or material other than that the workpiece or material is capable of being heated primarily by radiation of heat from the inductively heated crucible, and also, for material in contact with the inner wall of the crucible, by conduction of heat from the inductively heated crucible.

[0072] The foregoing embodiments do not limit the scope of the disclosed invention. The scope of the disclosed invention is covered in the appended claims.